# ERRATA[1]

for the third and fourth printings of
Doppler Radar and Weather Observations, Second Edition-1993
Richard J. Doviak and Dusan S. Zrnic’
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| Page | Para. | Line | Remarks: Paragraph 0 is any paragraph started on a previous page that carries over to the current page. A sequence of dots is used to indicate a logical continuation to existing words in the textbook (e.g., see errata for p.14; or that for p.76; etc.) |
|---|---|---|---|
| xix | | $\theta$ | modify definition to read: “is the zenith angle (Fig. 3.1); also the angle from the axis of a circularly symmetric beam (p. 34); also potential energy |
| 14 | 2 | 2 | change to read: “…index $n = c/v$ with height (or, because the relative permeability $\mu_r$ of air is unity, on the change of relative permittivity, $\varepsilon_r = \varepsilon/\varepsilon_o = n^2$, with height). |
| 17 | 1 | 2-6 | line 2, change “$T$=300 K” to “$T$=290 K”; line 4, change this equation to read: $N \approx 0.268\times(10^3 + 1.66\times10^2) \approx 312$; and line 6 change “1.000300” to “1.000312”. |
| 30 | 2 | 9 | replace the italicized “*o*” from the first entry of the word “oscillator” with a regular “o”, but italicize the “o” in the second entry of the word “*o*scillator” |
| | 3 | 7 | delete the parenthetical phrase |
| 34 | Eqs.3.2 | | replace $D$ with $D_a$ |
| 35 | 1 | 9 | at the end of the last sentence add: with origin at the scatterer. |
| | 2 | 10 | the equation on this line should read: |

1 Updates to the errata to the 3rd and 4th printings are periodically posted on NSSL’s website at nssl.noaa.gov. Click the links to Publications, Recent Books, and Errata 2nd edition, 3rd and 4th printings. Also posted are Supplements that clarify or extend the book text. The Dover Edition is a copy of the 1st and 2nd printings and errata to those printings, also at the same website, is not updated; for updates refer to this errata

$$\sigma_b = \sigma_{bm}\left(1 - \sin^2 \psi / \sin^2 \theta\right)^2 \cos^4[(\pi / 2)\cos\theta] / \sin^4 \theta$$

| | | | |
|---|---|---|---|
| | Eq.(3.6) | | and on the line after this equation, change "$K_m$" to "$K_w$" |
| 36 | 0 | 7 | delete "$\|K_m\|^2 \equiv$" |
| | | 9 | change the end of this line to read: "Ice water has a $\|K_w\|^2 \equiv$" |
| 40 | Eq.(3.14b) | | replace subscript "m" with "w" |
| 47 | Table 3.1 | | change title to read: "The *nex*t generation *rad*ar, NEXRAD (WSR-88D), Specifications"<br>change "Beam width" to "Beamwidth"<br>change footnote *b* to read: "Initially the first several radars transmitted circularly polarized waves, but now all transmit linearly polarized waves".<br>Change footnote *c* to read: "Transmitted power, antenna gain, and receiver noise power are referenced to the antenna port, and a 3 dB filter bandwidth of 0.63 MHZ is assumed. |
| 61 | Eq.(3.40b) | | place $\pm$ before $v_a$ |
| | 0 | 14 | last line change to "velocity limits (Chapter 7)." |
| 68 | 3 | 8 | change to read as: "or expected power $E[P(\tau_s)]$." |
| 68-69 | 4 | 1,10,12 | change "$\overline{P}(\tau_s)$" on these three lines to "$E[P(\tau_s)]$" |
| 71 | Eqs.(4.4a,b) | | insert $(1/\sqrt{2}\ )$ in front of the sum sign in each of these equations |
| | 3 | 6 | replace "p. 418" with "p. 498". |
| | Eq. (4.6) | | delete the first "2" |
| 72 | 0 | 4 | change $\overline{P}(\tau_s)$ to $E[P(\tau_s)]$ |
| | 2 | 1 | change $\overline{P}(\tau_s)$ to $E[P(\tau_s)]$ |
| | | 3 | remove footnote |
| 73 | Eq. (4.11) | | change "$\overline{P}(\boldsymbol{r}_0)$" to "$E[P(\boldsymbol{r}_0)]$". |

74-75 Eqs. (4.12), (4.14), (4.16): change "$\overline{P}(\boldsymbol{r}_0)$" to "$E[P(\boldsymbol{r}_0)]$".

| | | | |
|---|---|---|---|
| 75 | 1 | 6 | change to "$G(0) = 1$" |
| | 2 | 18 | change "$\overline{P}(\boldsymbol{r}_0)$" to "$E[P(\boldsymbol{r}_0)]$". |
| 76 | Fig.4.5 | | change second sentence in caption to read: "The broad arrow indicates sliding of...." |
| 77 | 0 | 12 | change "mean" to "expected" |
| | | 13 | change "$\overline{P}(\tau_s)$" to "$E[P(\tau_s)]$" |
| | Eq. (4.21) | | change "$\overline{P}(\tau_s)$" to "$E[P(\tau_s)]$" |
| | Eq. (4.22) | | delete $\equiv \lvert W(r) \rvert^2$ |
| 78 | Fig. 4.7 | | change the argument '$r$' in $\lvert W(r) \rvert^2$ to '$c\tau_s/2 - r$' |
| 82 | Eq.(4.31) | | delete the subscript "w" on $Z$ |
| | Eq.(4.32) | | delete the subscript "w" on $Z$ |
| | Eq. (4.34) | | change "$P(\bar{\boldsymbol{r}}_0)$" to "$E[P(\boldsymbol{r}_0)]$". |
| | Eq. (4.35) | | change "$\overline{P}(\text{mw})$" to "$E[P(\text{mw})]$" |
| | 1 | 9 | should read: ".. is the *reflectivity factor* of spheres." |
| 83 | Eq.(4.38) | | subscript "τ" should be the same size as in Eq.(4.37). |
| 84 | Eqs. (4.39), (4.43) | | change "$\overline{P}(\boldsymbol{r}_0)$" to "$E[P(\boldsymbol{r}_0)]$". |
| 85 | 0 | 4 | change "$\overline{P}(\boldsymbol{r}_0)$" to "$E[P(\boldsymbol{r}_0)]$". |
| | Problem 4.1 | | change "$\overline{P}$" to "$E[P]$" in two places. |
| 108 | 1 | 1 | change "stationary" to "steady" |
| | 1 | 11 | change "$d\overline{P}$" to "$E[dP]$". |
| | Eq. (5.42) | | change "$d\overline{P}(v)$" to "$E[dP(v)]$ |

| | | | |
|---|---|---|---|
| | | 15 | change "$\overline{P}(\mathbf{r}_0, v)$" to" $E[\Delta P(\mathbf{r}_0, v)]$" |
| | Eq.(5.43) | | change "$\overline{P}(\mathbf{r}_0, v)$" to" $E[\Delta P(\mathbf{r}_0, v)]$" |
| | 3 | 2-3 | change to read: "…..by new ones having different spatial configurations, *the estimates* $\hat{S}(\mathbf{r}_o, v)$ *of* …" |
| 109 | Eq.(5.45) | | change "$\overline{P}(\mathbf{r}_0)$" to "$E[P(\mathbf{r}_0)]$" |
| | 4 | 1 | add subscript "I" to $\overline{\eta}$ so it reads as "$\overline{\eta}_{\mathrm{I}}(\mathbf{r}_0)$" |
| | Eq.(5.46a) | | add subscript "I" to $\overline{\eta}$ on the left side of this equation. |
| | | | Change footnote "4" to read: "The overbar, without the subscript "I", denotes a reflectivity *and* $I_{\mathbf{n}}(\mathbf{r_0}, \mathbf{r_1})$ weighted spatial average." |
| 113 | 1 | 1-4 | change to read: "Assume scatterer velocity is the sum of steady $v_s(\mathbf{r})$ and turbulent $v_t(\mathbf{r},t)$ wind components. Each contributes to the width of the power spectrum (even uniform wind contributes to the width because radial velocities $v_s(\mathbf{r})$ vary across $V_6$; steady wind also brings new...." |
| | 2, 3 | 10, 3 | delete the sentences beginning on line 10 in paragraph 2 with "Furthermore, we assume..." and ending in paragraph 3, line 3 with "...scatterer's axis of symmetry)." |
| | Eq. (5.59a) | | change to: |

$$
\begin{aligned}
R(mT_s) &= E[V^*(\tau_s, 0)V(\tau_s, mT_s)] \\
&= E\left[\sum_i \sum_k F_i^*(0)A_i^*(0)F_k(mT_s)A_k(mT_s)\exp\{j(\phi_i - \phi_k - 4\pi v_k mT_s / \lambda\}\right] \qquad (5.59a) \\
&= \sum_k E[A_k^*(0)A_k(mT_s)F_k^*(0)F_k(mT_s)\exp\{-j4\pi v_k mT_s / \lambda\}]
\end{aligned}
$$

Following this equation the text to the end of the paragraph should read as follows:

Expectations of the off-diagonal terms of the double sum are zero because the phases ($\varphi_i - \varphi_k$) are uniformly distributed across $2\pi$; thus the double sum reduces to a single one. To simplify further analysis, assume that the scatterer's cross section is independent of its position and velocity, and that $F_k$ does not change appreciably [i.e., $F_k(mT_s) \approx F_k(0)$] while the scatterer moves during the time $mT_s$. Furthermore, assume $A_k$ varies randomly in time (i.e., a hydrometeor may oscillate or change its orientation relative to the electric field). Thus Eq. (5.59a) reduces to

$$R(mT_s) = \sum_k B_k(mT_s) \, | F_k |^2 \; E[\exp\{-j4\pi v_k mT_s / \lambda\}] \tag{5.59b}$$

where

$$B_k(mT_s) = E[A_k^*(0) A_k(mT_s)] \quad (\mathrm{m}^2)$$

Because $R(0)$ is proportional to the expected power $E[P]$, and because

$$E[P(\mathbf{r}_0)] = \sum_k \sigma_{bk} I(\mathbf{r}_0, \mathbf{r}_k) \tag{5.59c}$$

[i.e., from Eq. (4.11)], where $\sigma_{bk}$ is the expected backscattering of the $k^{\text{th}}$ hydrometeor, it follows that $B_k(0)$ is proportional to $\sigma_{bk}$ and thus $B_k(mT_s)$ gives the loss…."

| | | | |
|---|---|---|---|
| 114 | 2 | 2-4 | modify to read: "...mechanisms in Eq. (5.59b) act through product terms. Furthermore, the *k*th scatterer's radial velocity $v_k$ can be expressed as the sum of the velocities due to steady and turbulent winds that move the scatterer from one range position..." |
| | | 6-9 | delete these lines and replace with: "…Eq. (5.59b), the velocities $v_s(\boldsymbol{r})$ and $v_t(\boldsymbol{r}, t)$ associated with steady and turbulent winds can each be placed into separate exponential functions that multiply one another. Thus the expectation of the product can be expressed by the product of the exponential containing $v_s(\boldsymbol{r})$ and the expectation of the exponential function containing $v_t(\boldsymbol{r}, t)$; these exponential functions are correlation functions. The Fourier transform of $R(mT_s)$, giving the composite spectrum $S(f)$, can then be expressed as a convolution of the spectra associated with each of the three correlation functions. There are other de-correlating mechanisms (e.g., differential terminal velocities, antenna motion, etc.,) that increase the number of correlation functions and spectra to be convolved. It is shown that, …." |
| 115 | 3 | 1 | "R" in "$\mathrm{R_k}$" should be italicized to read "$R_{\mathrm{k}}$" |
| | | 9 | change "Eq. (5.59a)" to "Eq. (5.59b)" |
| | | 14 | Change these lines and Eqs. (5.64) to read: "Because the correlation coefficient can be related to the normalized power spectrum $S_n(f)$ by using Eq. (5.19), and because the Doppler shift $f = -2v/\lambda$, $\rho(mT_{\mathrm{s}})$ can be expressed as |

$$\rho(mT_s) = \int_{-\lambda/4T_s}^{\lambda/4T_s} \frac{2}{\lambda} E\left[S_n^{(f)}(-2v/\lambda)\right] e^{-j4\pi mT_s/\lambda} dv = \int_{-v_a}^{v_a} E\left[S_n(v)\right] e^{-j4\pi vmT_s/\lambda} dv \quad (5.64)$$

116 0 1-4 change these lines to read: where $S_n^{(f)}(-2v/\lambda)$ is the normalized power spectrum in the frequency domain folded about zero, $S_n(v)$ is the normalized power spectrum in the Doppler velocity domain, and the two power spectra are related as

$$S(v) = \frac{2}{\lambda} S^{(f)}(-2v/\lambda). \quad (5.65)$$

By equating Eq. (5.63) to Eq. (5.64), and assuming all power is confined within the Nyquist limits, $\pm\, v_a$, it can be concluded that

$$p(v) = E\left[S_n(v)\right]. \quad (5.66)$$

1 1-3 change to read: "Thus, for homogeneous turbulence, at least homogeneous throughout the resolution volume $V_6$, the *expected* normalized power spectrum is equal to the velocity probability distribution. Moreover, it is independent of reflectivity and the angular and range weighting functions.

1 3-7 Delete the last two sentences beginning with "Although, in deriving…."

116 2 15-21 the two sentences beginning with "Because the cited spectral ….." should be modified to read: "If turbulence, hydrometeor oscillation/wobble, and terminal velocities are locally homogeneous (i.e., statistically homogeneous over $V_6$) and independent spectral broadening mechanisms, it can be shown that the square of the composite velocity spectrum width $\sigma_{\mathrm{v}}^2$ can be expressed as the sum

$$\sigma_{\mathrm{v}}^2 = \sigma_{s\alpha}^2 + \sigma_{\mathrm{t}}^2 + \sigma_{\mathrm{o}}^2 + \sigma_{\mathrm{d}}^2. \quad (5.67)$$

where $\sigma_{s\alpha}^2$ is due to the combined effect of shear and antenna motion, $\sigma_d^2$ to different …."

23 this line should be changed to read as "…..airborne radar, $\sigma_{s\alpha}$ principally depends on antenna rotation and shear.

117 1 7 end this paragraph at the end of the sentence: "…to the beam center."

7-8 begin a new paragraph by modifying these lines to read: "If there is no radial velocity shear, and if the antenna pattern is Gaussian….."

Eq. (5.69) change to read:

$$\sigma_{s\alpha}^2 \rightarrow \sigma_\alpha^2 = (\alpha\lambda\cos\theta_e / 2\pi\theta_1)^2 \ln 2 \tag{5.69}$$

2 1 change this line to read: "Assume the beam is stationary. We shall prove that the term $\sigma_{s\alpha}^2 \rightarrow \sigma_s^2$ is composed of three…."

4-7 Modify these lines to read: "where the terms are due to shear of $v_s$ along the three spherical coordinates at $\mathbf{r}_0$. In this coordinate system (5.70) automatically includes…"

9 change to read: "the so-called beam-broadening term;...."

117-118; 3 Replace the text in this paragraph up to and including Eq. (5.75) with:

"Spherical coordinate shears of $v_s$ can be directly measured with the radar and it is natural to express $\sigma_s^2$ in terms of these shears. If the resolution volume $V_6$ dimensions are much smaller than its range $r_0$, and angular and radial shears are uniform, $v_s$ can be expressed as

$$v_s - v_o \approx k_\phi r_o \sin\theta_o(\phi - \phi_o) + k_\theta r_o(\theta - \theta_o) + k_r(r - r_o) \tag{5.71}$$

provided $\theta_1 << 1$ (radian) and $\theta_0 >> \theta_1$, where

$$k_\phi \equiv \frac{1}{r_o \sin\theta_o}\frac{dv_s}{d\phi}, \quad k_\theta \equiv \frac{1}{r_o}\frac{dv_s}{d\theta}, \quad k_r \equiv \frac{dv_s}{dr} \tag{5.72}$$

are angular and radial shears of $v_s$. Angular shears, defined as the Doppler (radial) velocity change per differential arc *length* (e.g., $r_o \sin\theta_0 d\varphi$), are present even if Cartesian shears are non-existent, and they are functions of $\mathbf{r}_0$. For example, if wind is uniform (i.e., has constant Cartesian components $u_0$, $v_0$, $w_0$),

$$\frac{dv_s}{d\phi} = (u_0\cos\phi_0 - v_0\sin\phi_0)\sin\theta_0; \frac{dv_s}{d\theta} = (u_0\sin\phi_0 + v_0\cos\phi_0)\cos\theta_0 - w_0\sin\theta_0;\ k_r = 0 \tag{5.73}$$

If reflectivity is uniform and the weighting function is product separable and symmetric about $\mathbf{r}_0$, substitution of Eq. (5.71) into Eq. (5.51) produces

$$\sigma_s^2(\mathbf{r}_0) = \sigma_{s\theta}^2 + \sigma_{s\phi}^2 + \sigma_{sr}^2 = k_\theta^2 r_0^2 \sigma_\theta^2 + k_\phi^2 r_0^2 \sigma_\phi^2(\theta_0)\sin^2\theta_0 + k_r^2\sigma_r^2. \tag{5.74}$$

Because lines of constant $\phi$ converge at the vertical, the second central moment $\sigma_\phi^2(\theta_0)$ of the two-way azimuthal power-pattern, for the elevation over azimuth type beam positioners used with weather radars, is $\sigma_\phi^2(\theta_0) = \sigma_\phi^2(\pi/2)/\sin^2\theta_0$, where $\sigma_\varphi^2(\pi/2)$ is the intrinsic azimuthal beamwidth; $\sigma_r^2$ is the second central moment of $|W(r)|^2$. For circularly symmetric Gaussian patterns,

$$\sigma_\theta = \frac{\theta_1}{4\sqrt{\ln 2}}\,; \quad \sigma_\phi(\theta_0) = \frac{\theta_1}{4\sqrt{\ln 2}}\frac{1}{\sin\theta_0} \tag{5.75}$$

118 0 after Eq. (5.76) add: "The above derivation ignored effects of beam scanning during the dwell time $MT_S$. If the beam scans at an azimuth rate $\alpha$, it can be shown that

$$\sigma_{s\alpha}^2 = \sigma_\alpha^2 + k_\theta^2 r_0^2 \sigma_\theta^2 + k_\phi^2 r_0^2 \sigma_{\phi e}^2(\pi/2,\alpha) + k_r^2 \sigma_r^2 \tag{5.77}$$

where $\sigma_{\phi e}(\pi/2,\alpha) = \theta_{1e}(\alpha)/4\sqrt{\ln 2}$, is the azimuthal beamwidth effectively broadened by antenna rotation during $MT_S$, and $\theta_{1e}(\alpha)$ is the effective one-way half-power azimuthal width, a function of $\alpha MT_s$ (Fig. 7.25).

125 1 1 replace "average" with "expected"

Eq. (6.5) append to this equation the footnote: "In chapter 5 $\rho$ is the complex correlation coefficient. Henceforth it represents the magnitude of this complex function."

4 5 remove the overbar on $P$, $S$, and $N$

126 0 1 change to read: "power estimate $\hat{P}$ is reduced……variance of the $P_k$.."

3 2-4 the second sentence, modified to read, "The $P_k$ values of meteorological interest...meeting this large dynamic range requirement", should be moved to the end of the paragraph 1

5 change "$\overline{P}$" to "$S$".

127 0 1-2 remove the overbar on $P$ in the three places

3 1 remove the overbar on $Q$

8 delete the citation "(Papoulis, 1965)"

| | | | |
|---|---|---|---|
| 128 | 1 | 8 | change "unambiguous" to "Nyquist" |
| | 2 | 4-7 | rewrite the second and third sentences after Eq. (6.12) as: "The variance of *S* estimated from *M* samples is calculated using the distribution given by Eq. (4.7) in which $S \equiv P$ (this gives, in Eq. (6.10), $\sigma_Q^2 = S^2$), and calculating $M_I$ from Eq. (6.12). Thus the standard deviation of an M-sample signal power estimate is $S/\sqrt{M_I}$ ." |
| | 3 | 1-2 | change to read "To estimate *S* in presence of receiver noise, we need to subtract....." |
| | | 4-9 | remove overbars on *S* and *N* |
| 129 | 0 | 5-6 | change last sentence to read: "....then the number of independent samples can be determined using an analysis similar to....." |
| 130 | Table 6.1 | | add above **"Reflectivity factor calculator"** the new entry "**Sampling rate",** and in the right column on the same line insert "0.6 MHz". Under "**Reflectivity factor calculator**", "Range increment" should be "0.25 km" and not "1 or 2 km". But insert as the final entry under "**Reflectivity factor calculator**" the entry "Range interval $\Delta r$", and on the same line insert "1 or 2 km" in the right column. |
| 136 | footnote | | change to read: "To avoid occurrence of negative $\hat{S}$ , only the sum in Eq. (6.28) is used but it is multiplied with $S\hat{N}R/(S\hat{N}R+1)$ " |
| 137 | 2 | 1 | delete "( $\sigma_{vn} > 1/2\pi$ )" |
| 142 | Eq.(6.42) | | place a caret |
| 155 | 3 | 3 | in section 6.8.5 line 3, change "Because" to "If" |
| 160 | 2 | 6 | change "unambiguous velocity " to "Nyquist velocity" |
| 171 | 0 | 3 | $T_s$ should be $T_2$ |
| 173 | 0 | 1 | change to read: "…velocity interval $\pm v_m$ for this…." |
| | Eq. (7.6b) | | place $\pm$ before $v_m$ |
| | 3 | 9-10 | this should read: "…the desired unambiguous velocity interval. An unambiguous velocity interval $v_{\mathrm{m}}$ =…" |

| | | | |
|---|---|---|---|
| | | 11 | change "unambiguous" to "Nyquist" |
| 182 | Eq.(7.12) | | $W_i W_{i+1}$ should be $W_i W_{i+l}$ |
| 197 | 1 | 1 | "though" should be "through" |
| | 2 | 4 | "Fig.3.3" should be "Fig.3.2" |
| 200 | Fig.7.28 | | Note the dashed lines are incorrectly drawn; they should extend from -26 dB at $\pm 2^o$ to -38dB at $\pm 10^o$, and then the constant level should be at -42 dB. |
| 201 | 0 | 2 | "Norma" should be "Norman" |
| | Eq. (7.36) | | change "$\overline{P}(r_0)$" to "$E[P(\mathbf{r}_0)]$" |
| 213 | 1 | | Change this paragraph to read: The Marshall-Palmer (M-P) data extend over a relatively short range of drop diameters (Fig. 8.3a). Earlier measurements (Laws and Parsons, 1943; Fig. 8.3b) that span a much larger range show that the drop size distributions (DSDs) at small drop diameters do not converge to a constant $N_0$ as suggested by Marshal and Palmer. The large increase in drop density at smaller diameters is also seen in the theoretical steady-state distributions derived by Srivastava (1971). |
| 222 | Eq. (8.18) | | the differential "d*D*" on the left side of Eq.(8.18) must be moved to the end of this equation. |
| 228 | 1 | 4 | change $Z_w$ to $Z_e$ |
| | Eq.(8.24) | | this equation should read as: $$Z_i = (\lvert K_w\rvert^2 / \lvert K_i\rvert^2)Z_e \qquad (8.24)$$ |
| | 2 | 6 | change to: "..to estimate the equivalent rainfall rate $R_s$ (mm/hr) from the..." |
| | | 7 | delete "with $Z_w = Z_e$" |
| 232 | 0 | 10-11 | change to: "...a microwave (i.e., $\lambda$= 0.84 cm) path, confirmed...." |
| 234 | Eq.(8.30) | | right bracket "}" should be matched in size to left bracket "{" |

| | | | |
|---|---|---|---|
| 248 | Eq.(8.57) | | parenthesis ")" needs to be placed to the right of the term "(b/a" |
| 249 | Eq.8.58 | | $\cos^2\delta$ should be $\sin^2\delta$; replace $k_o$ with $k$; $p_v$ and $p_h$ should be replaced with $p_a$ and $p_b$ respectively |
| | Eq.8.59a,b | | change the subscripts "h" to "b", and "v" to "a" |
| | 2 | 9 | change to read: "$p_a$ and $p_b$ are the drop's susceptibility in generating dipole moments along its axis of symmetry and in the plane perpendicular to it respectively, and $e$ its eccentricity," |
| | | 12-13 | rewrite as: "...symmetry axis, and $\Psi$ is the apparent canting angle (i.e., the angle between the electric field direction for "vertically" polarized waves, **v** in Fig.8.15, and the projection of the axis of symmetry onto the plane of polarization). The forward scattering........" |
| | | 17 | modify to read: "….$f_h = k^2 p_b$, and $f_v = k^2\ [(p_a - p_b)\sin^2\delta + p_b]$ (Oguchi, ....." |
| | 3 | 4-5 | Rewrite as: "Hence from Eqs.(8.58) an oblate drop has, for horizontal propagation and an apparent canting angle equal to zero, the following cross sections for h and v polarizations:" |
| 268 | Fig. 8.29 | | $\mathrm{LDR}_{hv}$ on the ordinate axis should be $\mathrm{LDR}_{vh}$ |
| | 0 | 1,4 | change $\mathrm{LDR}_{hv}$ to $\mathrm{LDR}_{vh}$ at the two places it appears in this paragraph. |
| 269 | Fig. 8.30 | | In the caption, change $\mathrm{LDR}_{hv}$ to $\mathrm{LDR}_{vh}$ at the two places it appears. |
| 277 | 0 | 16 | change "23000" to "230,000" |
| 289 | 2 | 3 | delete the sentence beginning with "In this chapter overbars…." |
| 298 | Fig.9.4a,b | | here and elsewhere in the text, remove periods in time abbreviations (i.e., should be: "CST", not C.S.T.") |
| 390 | 0 | 1 | change to read "along the path $\ell$ of the aircraft, and $S_{ij}(K_\ell)$ is the Fourier transform of $R_{ij}(\ell)$. In contrast...." |
| 393 | 1 | 11 | the subscripts on $R_{11}(0)$ should be changed to $R_{ll}(0)$; (i.e., so that it is the same as the subscripts on the second "$D$ " in line 19). |
| | Eq. (10.33) | | place subscript $l$ on $C$ so that it reads $C_l$. |
| 394 | 0 | 1 | change to read: "where $C_l^2$ is a dimensionless parameter with a value of about 2." |

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|---|---|---|---|
| | Eq.(10.37) | | change to read: $$R_{ii}(\rho, \tau_1 = 0) = R(0)[1 - (\rho / \rho_{oi})^{2/3}] \qquad (10.37)$$ |
| 398 | 1 | 12 | change to read: "…of the weighting function $I_n$, and $\Phi_v(\mathbf{K})$ is the spatial spectrum of point radial velocities." |
| | | 17 | change to read: "…antenna power pattern under the condition, $\theta_e = \pi/2 - \theta_0 \ll 1$, and…." |
| 404 | 2 | 1 | change to read: "….proportional to the radial component of turbulent kinetic energy,…" |
| | 4 | 7 | place an over bar on the subscript "u" in the next to last equation |
| 409 | 3 | 2 | change to read: "….must be interchanged with $\sigma_r$, and the second parameter (i.e., ½) in the argument of $F$ must be changed to 2. |
| | | 5,6 | change to read: "Using the series expansion for $F$ to first order in $1 - \dfrac{\sigma_\theta^2 r^2}{\sigma_r^2}$, the dissipation rate can be approximated by |
| 412 | 2,3 | 2,1 | delete the word "linear" in these two lines. |
| | 2 | 5 | change "polynomial surface" to "polynomial model" |
| | | 7 | change "surface" to "model" |
| 419 | Fig. 10.18 | | the "-5/3" dashed line drawn on this figure needs to have a -5/3 slope. Furthermore, remove the negative sign on "s" in the units (i.e., $m^3/s^{-2}$) on the ordinate scale; this should read ($m^3/s^2$). |
| 445 | 1 | 6 | delete "time dependence of the" |
| 453 | 1 | 10 | delete "(s)" from "scatterer(s)"; subscript "c" in $\rho_{c,\|\|}$ should be replaced with subscript "B" to read $\rho_{B,\|\|}$ |
| | | 12 | a missing subscript on $\rho_{,\perp}$ should be subscript "B" so the term reads: $\rho_{B,\perp}$ |
| Eqs. (11.105, &106) | | | the symbols $\|\|$ & $\perp$ should also be subscripts, along with "B", on the symbol "$\rho$" to read "$\rho_{B,\\|}$" and "$\rho_{B,\perp}$". |
| 454 | 0 | 6 | change "blob" and "blobs" to "Bragg scatterer" and "Bragg scatterers" |

| | | | |
|---|---|---|---|
| | Fig.11.11 | | caption should be changed to read: "........, a receiver, and an elemental scattering volume $dV_c$." |
| 456 Eq. (11.115) | | | bold "r" in the factor $W(\mathbf{r})$ needs to be unbolded |
| | Fig. 11.12 | | add a unit vector $\mathbf{a}_o$ drawn from the origin "**O**" along the line "$r_0$". |
| 458 | 2 | 4 | make a footnote after $\sqrt{2}$ to read: z′ is the projection of r′ onto the z axis; not to be confused with z′ in Fig.11.12 which is the vertical of the rotated coordinate system used in section 11.5.4. |
| 459 | Eq.(11.125) | | delete the subscript "c" in this equation, as well as that attached to $\rho_{ch}$ in the second line following Eq.(11.125) so that it reads "$\rho_h$". |
| 460 | 1 | 4-9 | delete the third to fifth sentences in this paragraph and replace with the following:<br>Condition (11.124) is more restrictive than (11.106); if (11.124) is violated the Fresnel term is required to account for the quadratic phase distribution *across the scattering volume*, whereas (11.106) imposes phase uniformity *across the Bragg scatterer*; this latter condition is more easily satisfied the farther the scatterers are in the far field (also see comments at the end of section 11.5.3). |
| 464 Fig. 11.14 | | | caption: the first citation is incorrect. It should read: "(data are from Röttger et al., 1981)". Furthermore, delete the last parenthetical expression: "(Reprinted with permission from ….)." |
| 468 | 2 | 11 | change "(11.109)" to "11.104" |
| 478 | 0 | 7 | Change to read:<br>"...the gain g. Then g, now the directional gain (Section 3.1.2), is related..." |
| 493 | 1 | | delete the last sentence and make the following changes:<br><br>1) change lines 2 and 3 to read: "... $C_n^2 = 10^{-18}\, m^{-2/3}$ (Fig.11.17), the maximum altitude to which wind can be measured is computed from Eq.(11.152) to be about 4.5 km."<br><br>2) change lines 4 and 5 to read: "…that velocity estimates are made with SNR = -19.2 dB (from Eq.11.153 for $T_s = 3.13 \times 10^{-3}$ s), and that $\sigma_v = 0.5$m $s^{-1}$, SD($v$) = 1 m $s^{-1}$, and a system temperature is about 200 K (section |

| | | |
|---|---|---|
| | | 11.6.3)." |
| 2 | 1-4 | change to read: "Assuming that velocities could be estimated at SNRs as low as -35dB (May and Strauch, 1989), the WSR-88D could provide profiles of winds with an accuracy of about 1 m $s^{-1}$ within the entire troposphere if $C_n^2$ values…" |
| | 8 | change "14" to "12" |
| | 9 | change "able to measure" to "capable of measuring" |
| 533 | 3 | change "Hitchfeld" to "Hitschfeld" |

## SUPPLEMENTS

The following supplements are provided at the indicated places to clarify and/or extend the text of "Doppler Radar and Weather Observations", Second Edition-1993.

Page Para. Line Remarks: Paragraph 0 is any paragraph started on a previous page that carries over to the current page.

Add to the List of Symbols:

| | |
|---|---|
| $E$[x] | Expected value of the random variable 'x'; also <x> |
| $\hat{x}$ | an $M$ sample estimate of $E$[x], |
| $\bar{x}$ | spatial average of 'x' |

| Page | Para. | Line | Remarks |
|---|---|---|---|
| 31 | Fig. 3.1 | | add $\theta_e$ to this figure. |
| 33 | 1 | 4 | change to read: …and often its intensity (i.e., power density) versus… |
| 34 | 0 | | Note that the one-way radiation pattern of the WSR-88D radar (the network radar used by the Weather Service in the USA) is well approximated with |

$$f^2(\theta) = \left( \frac{48.2 J_3(u)}{u^3} + \frac{0.32 J_1(u)}{u} \right)^2 \Big/ (1.16)^2 .$$

This agrees, down to about the -20 dB level, to within 2 dB of the pattern measured for NSSL's research WSR-88D at a wavelength of 0.111m. The pattern given by this equation is slightly broader (i.e., the 3 dB beamwidth calculates to about 1$^o$ whereas the measured width is about 0.93$^o$). This analytical expression is that obtained if the reflector's aperture is illuminated with a power density $[1-4(\rho/D_a)^2]^4$ on a uniform illumination level producing at the reflector's edge a power density 17.2 dB below the peak. The 1$^{st}$ and 2$^{nd}$ sidelobe levels, calculated from the above expression, are 34.2 and 48.4 dB below the peak lobe at about 1.7$^o$ and 2.5$^o$ respectively; sidelobes beyond 3$^o$ have relatively uniform levels that range from 56.3 (at 3$^o$) to 62 dB below the peak lobe at 10$^o$. Measured sidelobe levels (see Fig. 7.28), however, can be anywhere from a few dB to about 18 dB larger (the largest difference is at about 3$^o$). The increased measured levels are due to scatter and blockage from the feed and its supporting spars, distortions in the surface of the reflector, and scatter from objects (i.e., trees, buildings, etc.) on the antenna measurement range. Sidelobe levels are even larger (e.g., 25 dB above the theoretical level at 3$^o$) along measurement lines perpendicular to the feed supporting spars. But these enhanced levels, due to the blockage of radiation by the spars, are confined to relatively narrow angular sectors.

2 6 If the shape of the radiation pattern of a beam, not necessarily circularly symmetric, is well approximated by the product of two Gaussian functions, the maximum directional gain is

$$g_t' = \frac{1}{\sigma_\phi \sigma_\theta},$$

where $\sigma_\phi^2$ and $\sigma_\theta^2$, assumed to be much smaller than 1 rad$^2$, are the second central moments of the two-way pattern expressed in normal form. The two-way pattern is the product of the transmitted radiation pattern and the receiving antenna's field of view pattern. Typically the same antenna is used for both functions, and thus the two-way pattern is $f^4(\theta) f^4(\phi)$. For the circularly symmetric pattern of the WSR-88D, the two-way pattern is $f^4(\theta) = \exp\{-\theta^2 / 2\sigma_\theta^2\}$. In terms of the one-way 3-dB pattern width $\theta_1$, $\sigma_\theta = \theta_1 / 4\sqrt{\ln 2}$.

35 1 There are several definitions of cross sections. For example, $\sigma_d = \frac{S_r}{S_i} r^2$ is the *differential scatter cross section*; that is, it is the cross section *per unit* solid angle. Integration of $\sigma(\theta', \phi')$ over 4π steradians gives the *total scatter cross section* (see section 3.3).

36 0 2 Insert at the end of the first sentence: "It can be shown, using formulas presented in Section 8.5.2.4, that Eq. (3.6) has practical validity only if drops have an equivalent spherical diameter $D_e$ less than 2 mm. Drops having $D_e$ larger than 2 mm have backscatter cross sections differences larger than about 0.5 dB for horizontally and vertically polarized waves (i.e., $\sigma_h > 1.1\sigma_v$)."

38 0 1-2 change to read: "…flows in the forward or backward directions.

1 4 add at the end of this paragraph: "Furthermore, Probert-Jones (1984) demonstrated that internal resonances in electrically large low-loss spheres can generate greatly enhanced scatter in both the forward and backward directions.

42 Fig. 3.5 Caption: Because there is considerable confusion concerning the use of the unit dBZ, and because some writers use dBz for the decibel unit of reflectivity factor $Z$, we present the following comment:

The logarithm unit decibel, abbreviated dB, is related to the less used unit "bel", named in honor of Alexander Graham Bell (1847-1922). The dB has been accepted widely as a "unit" (e.g., Reference Data for Radio Engineers, 5th Edition, Howard W. Sams, publisher, division of ITT, p.3-3). Appendages to dB have been *accepted in the engineering field* to refer the dB unit to a reference level of the parameter being measured; e.g., dBm is the decibel unit for 10 $\log_{10}$ P where P is the power referenced to 1 milliwatt (e.g., Reference Data for Radio Engineers, 5th Edition, op. cit., p.3-3). The parameter dBZ *has been accepted by the AMS* as the symbol for the "unit" decibel of reflectivity factor referred to 1 $mm^6m^{-3}$ (Glossary of Meteorology, 2nd Edition, 2000, American Meteorological Society).

44 3 4 Blake has more recently published (1986, in "Radar range performance analysis", 2nd ed., ARTECH House, Norwood, MA.) new values of attenuation in gases. For example, at $\lambda = 10$ cm, $r = 200$ km, $\theta_e = 0^o$, the two way loss is about 0.3 dB larger than that given in Fig.3.6.

56 Eq. (3.34) If the beam is passing through clouds and storms, Eq. (3.34) should be replaced by

$$T_s' = \left(1 - \frac{1}{\ell_c}\right)(1 - \chi + \chi\eta_r)T_c + \frac{1-\chi}{\ell_c}T_s + \chi(1-\eta_r)T_g + \frac{\chi\eta_r}{\ell_c}T_s$$

where $\ell_c$ and $T_c$ are the cloud's attenuation and temperature.

57 Fig. 3.11 For completeness, the ordinate should be labeled "Sky noise temperature $T_s$ (K)"

68 3 8 add: "The expected value is obtained by averaging over an ensemble of scatterer configurations having the same statistical properties (e.g., reflectivity factor)."

The expectation operator $E$[x] in this book is used for ensembles of a variety of variables (e.g., velocity fields $v(\mathbf{r},t)$, scatterer configurations $\xi$, and backscatter cross sections σ). If the statistics are stationary, and assuming there is a velocity field that moves the scatterers, the expectation can be replaced with a time average. If statistics are not stationary, then the ensemble average must be made over $\xi$, and in this section we could have appended the subscript $\xi$ to have $E_\xi[x]$ to emphasize this fact and to avoid subsequent possible confusion.

71 2, 3 An explanation for the √2 factors in Eqs. (4.4) and (4.6), and how power is related to $\sigma^2$ might be helpful. Because a lossless receiver is assumed, the sum of powers in the *I* and *Q* channels must equal the power at the input to the receiver (i.e., the synchronous detectors in Fig. 3.1). Because we have assumed the amplitude of the echo voltage at the receiver's input is *A* (e.g., Eq. (2.2b)), the amplitude of the signal in the *I* and *Q* channels must

be $A/\sqrt{2}$. Furthermore, we can determine from Eq. (4.5) that the rms values of $I$ and $Q$ voltages equals σ (i.e., $I_{\mathrm{rms}} = Q_{\mathrm{rms}} = \sigma$). Thus the average power in each of the channels is $\sigma^2$, and the sum of the average powers in these two channels is $2\,\sigma^2$ which equals the expected power E[P] at the input to the receivers. The constants of proportionality (i.e., impedances) that relate voltage to power are assumed the same at all points in the receiver (e.g., at inputs to the $I$ and $Q$ channels).

72 2 1 here and in Eq. (4.8), we need to distinguish the expectation operator "$E$[x]" used in section 4.2 and 4.3, which strictly applies to an ensemble of scatterer configurations, from the expectation over the scatterer's cross section. Thus we could append the subscript $\sigma$ to the expectation operator in these first four lines of Section 4.4 and write $E_\sigma[x]$ which applies to each scatterer. However, when we deal with an number of scatterers we also need to take an ensemble average over scatterer configurations $\xi$. That is, the expectation operator in Eq. (4.9a) is performed over both $\sigma$ and $\xi$ (or over time if statistics are stationary). This interpretation carries throughout the book.

74 1 4 change to read: "….to its range extent, and if the polar axis of the spherical coordinate system (Fig. 3.1) is aligned with the beam axis (i.e., $\theta_0 = 0$), we can approximate Eq. (4.11) by…"

8 change to read: "…by a Gaussian shape, $f^4(\theta) = \exp(-\theta^2 / 2\sigma_\theta^2)$, we can show…"

10 change to read: "where $\theta_1 = 4\sigma_\theta\sqrt{\ln 2} << 1$ is the 3-dB…."

79 0 8 add at the end of this paragraph: Range $r_0$ is the range to the center of the radar's resolution volume defined in Section 4.4.4.

95 Eq. (5.17) Note that this equation is a biased estimate of the autocorrelation $R(l)$. To obtain an unbiased estimator, replace the $M^{-1}$ multiplier with $(M-1)^{-1}$.

106-112 Because sections 5.2 and 5.2.1 stipulate that the velocity field is steady (i.e., time independent) we should, in these two sections, append the subscript 's' to '$v$' to be consistent with later notation (i.e., errata on p. 113, line 1), and to emphasize that '$v$' is a steady wind.

108-110 The expectation operator $E$[x] in these pages strictly apply to an ensemble of scatterer configurations or, if statistics are stationary, to a time average.

| | | | |
|---|---|---|---|
| 112 | 2 | 10-12 | change to read: "…turbulence, etc.) act independently as we now demonstrate." |
| 114 Eq.(5.59b) | | | follow this equation in the errata with the following explanatory comment: "The expectation operation in Eq.(5.59b), could be written as $E_\xi$ to indicate the expectation is over an ensemble ξ of scatterer configurations as discussed on p.108. Furthermore, it would be clearer if we replaced $R_k(mT_s)$ in this equation and the one that follows it, with $B_k(mT_s)$ because $R_k(mT_s)$ has units of $m^2$, whereas $R(mT_s)$ is power. |
| Eq.(5.59c) | | | Strictly for clarity, this equation should be written as $$\mathrm{E}_\xi[P] = \sum_k \mathrm{E}_\sigma[\sigma_{bk}] I(\mathbf{r_0}, \mathbf{r}_k)$$ Because $P$ and $\sigma_{bk}$ are random variables; $P$ fluctuates as scatterers reconfigure themselves, and $\sigma_{bk}$ fluctuates as the hydrometeor oscillates/wobbles. The subscript ξ indicates an ensemble average over various scatterer configurations; it also could be a time average if the statistical parameters are stationary. |
| | 0 | 8 | change to read: "…where $\sigma_{bk}$ is the expected backscattering cross section of the $k^{th}$ hydrometeor (expectations computed over the ensemble of cross sections for the $k^{th}$ scatterer), it follows … |
| 116 | | | At the end of section 5.2, add the following paragraph: In this section we assumed scatterers follow exactly the air motion. But usually scatterers are hydrometeors that fall in air, have different fall speeds because of their different sizes, and change orientation, and vibrate (if they are liquid). These hydrometeor characteristics broaden the Doppler spectrum associated with the velocity field increasing $\sigma_v^2(\vec{r}_o)$ obtained from Eq. (5.51). |
| 118 | 0 | | after Eq. (5.75): It should be noted that as $\theta_0 \to 0$, the angular shears in Eq. (5.74) should be replaced by $k_\theta$ along the two principal axes of the beam pattern. For example, if the beam is circular symmetric and $\theta_0 = 0$, $\sigma_s^2 = r_o^2\sigma_\theta^2[k_\theta^2(\phi = 0) + k_\theta^2(\phi = \pi/2)] + (\sigma_r k_r)^2$. <br><br> After Eq. (5.76): It should be noted that if the receiver bandwidth $B_6$ is much larger than the reciprocal of the pulse width τ, $\sigma_r^2 = \frac{1}{12}\left(\frac{c\tau}{2}\right)^2$. |
| 125 | 2 | 1 | change to read: "It was explained in Section 5.2.2 that weather…." |

128, Eq.(6.13): this equation is valid when signal power is much stronger than noise power. The following text gives the standard deviation of the Logarithm of *Z*(dBZ) estimates as a function of Signal-to-Noise ratio and could replace paragraph 3 on p.128.

To estimate *Z* in presence of receiver noise, we need to subtract receiver noise power *N* from the signal plus noise power estimate $\hat{P}$. Thus the reflectivity estimate is $\hat{Z} = \alpha\hat{S} = \alpha(\hat{P} - N)$ where $\hat{P}$ is a uniformly weighted *M* sample average estimate of the power *P* at the output of the square law receiver (as in the WSR-88D), *N* is the receiver noise power, and *α* is a constant calculated from the radar equation. Because *N* is usually measured during calibration, many more samples are used to obtain its estimate. Therefore its variance is negligibly small, and the noise power estimate can safely be replaced with its expected value *N*. *Z* is usually expressed in decibel units; that is, $\hat{Z}(dBZ) = 10\log_{10}\hat{Z} = 10\log_{10}(\alpha\hat{S})$ where $\hat{Z}$ is expressed in units of mm$^6$ m$^{-3}$. The error in decibel units is now derived. Let $\hat{S}$, the *M* sample estimate of signal power, be expressed as $\hat{S} = S + \delta S$ where $\delta S$ is the displacement of $\hat{S}$ from *S*. Thus

$$\hat{Z}(dBZ) = 10\log_{10}(\alpha S) + 10\log_{10}\left(1 + \frac{\delta S}{S}\right) = Z + \delta Z(dBZ) \qquad (6.13a)$$

For sufficiently larger *M*, $\delta S / S$ is small compared to 1, and hence the second term can be expanded in a Taylor series. Retaining the dominant term of the series, the estimated reflectivity is well approximated by

$$\hat{Z}(dBZ) \approx Z + 4.34\left(\frac{\hat{S}}{S} - 1\right). \qquad (6.13b)$$

Because the first term and the constant 4.34 are not random, the standard error in the estimate is simply $S.D.[\hat{Z}(dBZ)] = 4.34\,S.D.[\hat{S}/S]$. Because $\hat{S} = \hat{P} - N$ where *N* is a known constant (for a correctly calibrated radar), $S.D.[\hat{S}] = S.D.[\hat{P}] = P/\sqrt{M_I} = (S+N)/\sqrt{M_I}$, where $M_I$ is the number of independent signal plus noise power samples. Hence

$$S.D.[\hat{Z}(dBZ)] = \frac{4.34(S+N)}{S\sqrt{M_I}} \qquad (6.13c)$$

The number of independent samples $M_I$ that are contained in the *M* sample set, can be calculated from (6.12) in which $\rho_s(mT_s)$ is replaced by $\rho_{s+n}(mT_s)$ the magnitude of the correlation coefficient of the signal plus noise samples.

Using (6.4), the correlation of signal plus noise for a Gaussian shaped signal spectrum and a white noise spectrum, normalizing it by $S + N$ to obtain the correlation *coefficient* of the input signal plus noise power estimates, the correlation coefficient at the output of the square law receiver, can be written as

$$\rho_{s+n}(mT_s) = \left( \frac{S}{S+N} \exp\{-2(\sigma_{vn}\pi m)^2\} + \frac{N}{S+N}\delta_m \right)^2 \tag{6.13d}$$

Under the condition that $\sigma_{vn} >> M^{-1}$, (i.e., the spacing between spectral lines is much smaller than the width of the spectrum), the sum in (6.12) can be replaced by an integral. Furthermore, if $M$ is large so that $\rho_{s+n}(mT_s)$ is negligibly small at $MT_s$, the limits on the integral can be extended to infinity. Evaluation of this integral under these conditions yields

$$M_I = \frac{\left(1+\frac{S}{N}\right)^2 M}{1 + 2\frac{S}{N} + \frac{(S/N)^2}{2\sigma_{vn}\sqrt{\pi}}} \tag{6.13e}$$

The formula for calculating the standard error in estimating $Z$(dB$Z$) as a function of $S/N$ is obtained by substituting (6.13e) into (6.13c) yielding

$$S.D.[\hat{Z}(dBZ)] = \frac{4.34}{\sqrt{M}}\frac{N}{S}\left(1 + 2\frac{S}{N} + \frac{(S/N)^2}{2\sigma_{vn}\sqrt{\pi}}\right)^{1/2} dB \tag{6.13f}$$

136 4 1-5 The form of Eq.(6.29) was first presented by Rummler (1968). *But this form does not follow directly from Eq.(6.27) as is stated in the sentences preceding Eq.(6.29).* Thus it would be more proper to change these lines to read:

"If spectra are not Gaussian, Rummler (1968) has derived an estimator valid for small spectrum widths (i.e., $\sigma_{vn} << 1$). This estimator is

(6.29)

At large widths Eq. (6.29) has an asymptotic ($M \to \infty$) negative bias which causes an underestimate of the true spectrum width (Zrnić, 1977b), whereas ....... spectrum is Gaussian)"

Added Reference:

Rummler, W. D. (1968), Introduction of a New Estimator for Velocity Spectral Parameters. *Technical Memorandum, April 3, 1968.* Bell Laboratories, Whippany, New Jersey 07981.

195 2 1-3 change to read: "Three parameters of interest…… integration, (2) the effective beamwidth, and (3) the effective pattern shape."

195-196 To be consistent with notation used elsewhere, and because on these pages we exclusively use the term "effective" instead of "apparent" when we describe patterns broadened by azimuthal scanning, use the subscript "e" instead of "a" on $f_a(\phi - \phi_0)$ and $\phi_a$.

196 1 1&7 replace $\phi_a$ with $\theta_{1e}$. (*note that* $\phi_a$ *is defined in Eq. 7.33 as the location of the maximum of the effective pattern, and as suggested here,* $\theta_{1e}$ *is the effective one-way half-power beamwidth. It would avoid confusion and make sense to change* $\phi_a$ *to* $\theta_{1e}$ *to be consistent with* $\theta_1$ *the one-way half-power beamwidth of the intrinsic pattern)*

1 at the end of this paragraph add the sentence: "If $\alpha MT_s \leq \theta_1$, the effective normalized pattern retains a Gaussian shape, but if $\alpha MT_s >> \theta_1$, the pattern shape is roughly trapezoidal having amplitude $(\alpha MT_s)^{-1}$, and a one-way half-power width of about $\alpha MT_s$."

2 3&5 replace $\phi_a$ here and in Fig. (7.25) with $\theta_{1e}$.

255 1 2 Recent data from a disdrometer show as much as a factor of 3 error

391 0 2 it should be noted that the correlation scale $\rho_0$ is not the same as the integral scale $\rho_I$ which is defined as

$$\rho_I = \int_0^\infty \frac{R(\rho)}{R(0)} d\rho$$

For the correlation function given by Eq. (10.19), $\rho_0$ is related to $\rho_I$ as

$$\rho_I = \frac{\Gamma(v + 0.5)\Gamma(0.5)}{\Gamma(v)} \rho_0$$

398 Section 10.2.1: we introduce the variable $\Phi_v(\mathbf{K})$, the spatial spectrum of point velocities, in Eq.(10.46) but define it in the paragraph following its introduction (i.e., in Eq. 10.48). We should label (10.48) as (10.46), and place it before Eq.(10.46) and label it as (10.47). Other adjustments should be made to correct equation numbers; these should be few.

399 0 1 add the parenthetical phrase "(i.e., spectra of radial velocities along a radial and transverse to the direction of advecting turbulence)

403 1 6 For a fuller explanation of the steps in Section 10.2.2, and using notation consistent with that used earlier in the text, we offer the following revision of section 10.2.2:

In this section we define the relationship between the variance of radial velocities at a *point* and the expected spectrum width measured by radar (Rogers and Tripp, 1964). Let the variance of the radial velocity $v(\boldsymbol{r}, t)$ at a point be $\sigma_p^2$. This variance is the sum of the variance at all velocity scales and is defined by the equation,

$$\sigma_p^2 = E_v[v^2(\boldsymbol{r},t)] - E_v^2[v(\boldsymbol{r},t)] \tag{10.55}$$

where $E_v[x]$ indicates an expectation, or an average over an <u>ensemble of velocity fields</u>, all having the same statistical properties. Assume that steady wind is not present, the radar beam is fixed, and hydrometeors do not oscillate or wobble and are perfect tracers of the wind. In this case, turbulence is the only mechanism contributing to spectral broadening, and it is a random variable having zero mean (i.e., $E_v[v(\boldsymbol{r}, t)] = 0$).

The second central moment, $\sigma_{\mathrm{v}}^2$, of the Doppler spectrum associated with turbulence can be obtained from Eq. (5.51). Although Eq. (5.51) was derived under the assumption that $v(\boldsymbol{r}, t)$ is steady, this equation can be applied to the time varying wind produced by turbulence. But then $\sigma_{\mathrm{v}}^2$ would be a time varying quantity because $v(\boldsymbol{r}, t)$ is now a time dependent variable. Replacing $\sigma_v^2$ in Eq. (5.51) with $\overline{\sigma_t^2(\boldsymbol{r},t)}$ for pure turbulence, we obtain,

$$\overline{\sigma_t^2(\boldsymbol{r},t)} = \overline{[v(\boldsymbol{r},t) - \overline{v(\boldsymbol{r},t)}]^2} = \overline{v^2(\boldsymbol{r},t)} - \overline{v(\boldsymbol{r},t)}^2 \tag{10.56}$$

where $\overline{\sigma_t^2(\boldsymbol{r},t)}$ is the expected instantaneous second central moment of the Doppler spectrum associated with turbulence. Although $\overline{\sigma_t^2(\boldsymbol{r},t)}$ is a function of $\boldsymbol{r}_0$, the location of the $V_6$, we have omitted $\boldsymbol{r}_0$ to simplify notation; nevertheless, the argument $\boldsymbol{r}_0$ is implicit in $\overline{\sigma_t^2(\boldsymbol{r},t)}$. The overbar denotes a spatial average weighted by the normalized function $H_n(\boldsymbol{r}_0,\boldsymbol{r})$ where

$$H_n(\boldsymbol{r}_0,\boldsymbol{r}) = \frac{I(\boldsymbol{r}_0,\boldsymbol{r})\eta(\boldsymbol{r})}{\iiint I(\boldsymbol{r}_0,\boldsymbol{r})\eta(\boldsymbol{r})dV}$$

is a combination of reflectivity $\eta(\boldsymbol{r})$ and antenna pattern weights. Because the focus in this section is on the time changing velocity field we assume $\eta(\boldsymbol{r})$ to be time independent.

Note that $\overline{\sigma_t^2(\boldsymbol{r},t)}$ is the <u>expected</u> instantaneous second central moment of the

Doppler spectrum. In this case, however, the expectation, $E_\xi[x]$, is over ensembles of scatterer configurations $\xi$ (Doviak and Zrnic, 1993, p.108) each having the same velocity field, whereas the expectation in Eq. (10.55) is taken over ensembles of velocity fields. Different scatterer configurations can be obtained by reshuffling scatterer locations. Although we can, in principle, freeze the velocity field, scatterers can have differential motion that results in a changing scatterer configuration. This in turn results in changes in the weather signal, and thus fluctuations of the estimates $\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}$ of $\overline{\sigma_t^2(\boldsymbol{r},t)}$. The circumflex ^ denotes the estimate made from weather signal samples obtained during a dwell-time, and '$t_n$' denotes the $n^{\text{th}}$ dwell-time, the short time span of duration $MT_s$, typically less than 1s.

Thus, expectations $E_\xi[x]$ can be made, at least in principle, over ensembles of $\xi$ while $\hat{v}(\boldsymbol{r},t_n)$ is frozen. We use the variable $t_n$ in place of $t$ to emphasize that estimates are made from data collected during short dwell-times wherein the velocity field can be considered to be fixed. Furthermore, even though estimate variance associated with different configurations of scatterers is removed by a $\xi$ average, we retain the circumflex '^' to emphasize the estimated value in this section pertains to one member of the ensemble of velocity fields at the $n^{\text{th}}$ dwell-time.

The time dependence of $\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}$ (i.e., $E_\xi[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}]$; henceforth the expectation over $\xi$ will not be explicitly shown) is also due to changes of shear, principally at turbulence scales large compared to $V_6$. That is, large scale turbulence contributes a time varying shear component to $\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}$, and it can also cause significant fluctuations of $\overline{\hat{v}(\boldsymbol{r},t_n)}$. Usually we are not interested in the detailed time dependencies of $\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}$ or $\overline{\hat{v}(\boldsymbol{r},t_n)}$, but in their statistical properties such as their mean or expected values, (e.g., $E_v[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}]$), their auto-correlation, etc. Furthermore, we shall show how $E_v[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}]$ is related to the energy density $E$ of turbulence.

The variance of the $H_n(\boldsymbol{r})$ weighted Doppler (i.e., radial) velocity $\overline{\hat{v}(\boldsymbol{r},t_n)}$ is, by definition, given by

$$\mathrm{var}\left[\overline{\hat{v}(\boldsymbol{r},t_n)}\right] \equiv E_v\left[\overline{\hat{v}(\boldsymbol{r},t_n)}^2\right] - E_v^2\left[\overline{\hat{v}(\boldsymbol{r},t_n)}\right] \equiv \sigma_{\bar{v}}^2(t_n). \tag{10.57a}$$

For pure turbulence, $E_v\left[\overline{\hat{v}(\boldsymbol{r},t_n)}\right] = 0$ and thus

$$\sigma_{\bar{v}}^2(t_n) = E_v\left[\overline{\hat{v}(\boldsymbol{r},t_n)}^2\right]. \tag{10.57b}$$

By taking the velocity ensemble average of Eq. (10.56), substituting Eq. (10.57b) into it, we obtain, after commuting ensemble and spatial averages (i.e., $E_v\left[\overline{v^2(\boldsymbol{r},t_n)}\right] \equiv \overline{E_v[v^2(\boldsymbol{r},t_n)]}$),

$$E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]+\sigma_{\bar{v}}^2(t_n)=\overline{E_v[\hat{v}^2(\boldsymbol{r},t_n)]}. \tag{10.58a}$$

The weighted spatial average of $E_v[\hat{v}^2(\boldsymbol{r},t_n)]$ is, by definition,

$$\overline{E_v[\hat{v}^2(\boldsymbol{r},t_n)]}=\int_V E_v[\hat{v}^2(\boldsymbol{r},t_n)]H_n(\boldsymbol{r}_0,\boldsymbol{r})dV \tag{10.58b}$$

The derivation leading to Eq. (10.58) does not require turbulence to be statistically stationary, homogeneous, or isotropic. That is, Eq. (10.58a) relates the expected value of the second central moment of measured Doppler spectra (i.e., measured estimated with short dwell-times), and the variance of the mean Doppler velocity, to the $H_n(\boldsymbol{r}_0,\boldsymbol{r})$ weighted spatial average of the expected value of the second central moment of the <u>radial</u> component of turbulence at <u>each</u> point $\boldsymbol{r}$ and $t_n$. This is in agreement with results of Rogers and Tripp (1964).

These results apply to estimates of the Doppler velocity and second central moments made with any dwell-time. If longer dwell-times are used, $E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]$ increases because velocity components associated with large scale turbulence have time to evolve within the resolution volume and be adequately sampled. On the other hand, the variance $\sigma_{\bar{v}}^2$ of the mean Doppler velocity decreases as dwell time increases, and it vanishes in the limit of an infinite dwell time. In this limit, $\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}$ solely measures the spatial average of the weighted distribution of turbulence at each point.

10.2.2.1 Estimate variance due to changes in scatterer configuration

It should be noted that the variance, $\sigma_{\bar{v}}^2(t_n)$, does not include the variance associated with the statistical uncertainty due to changing scatterer configurations. Nevertheless, variance (e.g., that discussed in Chapter 6) associated with the weather signal fluctuations due to changes in the scatterer configuration can be significant, and it needs to be included in any rigorous analysis of radar measurements of turbulence.

For example, in addition to the variance of $\overline{\hat{v}(\boldsymbol{r},t_n)}$ due to the time changing velocity field, we have additional variance associated with the random location of scatterers (i.e., the time dependence of the true $\overline{\hat{v}(\boldsymbol{r},t_n)}$ differs from the time dependent $\overline{\hat{v}(\boldsymbol{r},t_n)_R}$ estimated with radar). Here $\overline{\hat{v}(\boldsymbol{r},t_n)}$ is the weighted velocity irrespective of the scatterer configuration.

Even if $\hat{v}(\boldsymbol{r}, t_n)$ was a constant independent of time, the radar estimates $\overline{\hat{v}(\boldsymbol{r}, t_n)_R}$ would be fluctuating due to the fact that scatterers move continuously to new locations for the same velocity field. That is, there is an evolving configuration of scatterers, and each configuration of scatterers produces a different weather signal sample from which $\overline{\hat{v}(\boldsymbol{r}, t_n)}$ is estimated. In general, time fluctuations of estimates are due to both a changing velocity field and a changing configuration of scatterers.

To illustrate, assume a constant wind that carries scatterers along range arcs. In this case, the radial velocity field $\overline{\hat{v}(\boldsymbol{r}, t_n)} = 0$. Nevertheless, radar estimates of $\overline{\hat{v}(\boldsymbol{r}, t_n)}$ are time varying and random; this is so because the scatterers' configuration within $V_6$ continually changes as new scatterers enter $V_6$, and others leave it. That is, the In-phase, *I*, and Quadrature, *Q,* components of the weather signal are still Gaussian distributed random variables as shown in Fig. 4.4a. In other words, although the mean or expected Doppler velocity is zero, the time sequence of the *I, Q*, samples will randomly move in the *I, Q* plane, and Doppler velocity estimates made with a small number of samples (e.g., two) can have non zero values.

The changes of *I, Q* from sample pair to sample pair can be relatively small if the sample pair spacing is short compared to the correlation time $\tau_c$ of the weather signals, and if the intra-pulse spacing $T_s \ll \tau_c$. The weather signal correlation time $\tau_c$, approximately equal to the time required to flush $V_6$ with new scatterers, is not necessarily equal to the correlation time of the velocity field; in our simple illustration the correlation time of the velocity field is infinite. The non zero velocity estimates, calculated from pairs of *I, Q* samples, are uncorrelated if the pair spacing is longer than $\tau_c$. Only with a long time average will these velocity estimates average to 0.

These arguments, applied to the radar estimates of $\overline{\hat{v}(\boldsymbol{r}, t_n)}$, can also be applied to show that the $\xi$ expectation of the radar estimates $\overline{\hat{\sigma}_t^2(\boldsymbol{r}, t_n)_R}$ {i.e., $E_\xi\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r}, t_n)_R}\right]$} equals $\overline{\hat{\sigma}_t^2(\boldsymbol{r}, t_n)}$.

10.2.2.2 Homogeneous turbulence

If turbulence is homogeneous over the region where the weighting functions contribute significantly (i.e., turbulence is locally homogeneous), Eq. (10.58b) shows that $\overline{E_v[\hat{v}^2(\boldsymbol{r}, t_n)]} = \sigma_p^2(t_n)$, the "point-measured variance" (Frisch and Clifford, 1974; the following paragraph will clarify what is meant by "point-measured variance"). The radial component of the turbulent energy density at a point is, $E_r = \frac{1}{2}\gamma\sigma_p^2$, where $\gamma$ is the air mass density. Using Eq. (10.58a), and noting that $\overline{E_v[\hat{v}^2(\boldsymbol{r}, t_n)]} = \sigma_p^2(t_n)$, we can then relate $E_r$ to radar measurements as

$$\mathsf{E}_r = \frac{1}{2}\gamma\sigma_p^2(t_n) = \frac{\gamma}{2}\left\{E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right] + \sigma_{\bar{v}}^2(t_n)\right\}. \tag{10.59}$$

If turbulence is isotropic, the total turbulence energy density $\mathsf{E} = 3\,\mathsf{E}_r$.

Eq. (10.59), establishes a relation between the radial component of the "point-measured" turbulent energy density and the second central moment of the Doppler spectrum associated with turbulence, but it requires turbulence to be *locally* homogeneous although not isotropic or stationary. Therefore, the "point" under discussion is, in reality, a collection of points over the entire resolution volume wherein turbulence is assumed to have the same statistical properties at each point. Section 10.2.2.3 presents results for the case where turbulence is inhomogeneous.

Eq. (10.59) demonstrates that the energy density of the radial component of "point-measured" homogeneous turbulence can be calculated from the sum of the expected value of the second central moment, $E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]$, and the variance, $\sigma_{\bar{v}}^2 = E_v\left[\overline{\hat{v}(\boldsymbol{r},t_n)}^2\right]$, of the mean Doppler velocity estimates. It also shows how that energy is partitioned between large and small scales of turbulence; $\sigma_{\bar{v}}^2$ is principally due to large scale turbulence whereas $E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]$ is principally due to small scale turbulence.

If the radial component of turbulence has a -5/3rds power law vs wavenumber $K = 2\pi/\Lambda$ for all wavelengths $\Lambda$ of the spectrum of turbulence, and if the dimensions of $V_6$ are the same in all directions (i.e., $\sigma_\theta r_o = \sigma_\phi(\theta_0) r_o = \sigma_r$; section 5.3), it can be shown that turbulence from all $\Lambda \le L_c \equiv \sigma_\theta r_o$, the characteristic size of $V_6$, contributes only about 20% to $E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]$. Thus, although some portion of $E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]$ is due to small scales, most of its contribution comes from turbulence on wavelengths large compared to $L_c$; this appears at variance with previously published interpretations. For example, if the weighting function is uniform, as stipulated by Rogers and Tripp (1964), across $V_6$ having dimensions $LxLxL$, only 36% of $E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]$ is due to turbulence from all $\Lambda \le L$. This contradicts Rogers and Tripp (1964) statement that $E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]$ "receives spectral contributions mainly from the wavelengths shorter than the dimensions of $V_6$".

Large scale (i.e., large compared to $V_6$ dimensions) turbulence shifts the Doppler spectrum along the velocity axis so that the single spectrum mean Doppler velocity changes from one spectrum to the next. Thus to estimate $E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r},t_n)}\right]$ we need to average the second central moments calculated about each of the fluctuating means. For stationary and/or globally homogeneous turbulence, expectations can be obtained from averages over time and/or space (i.e., at different $\boldsymbol{r}_0$ locations).

10.2.2.3 Inhomogeneous turbulence

It is not necessary to assume turbulence is homogeneous (as we did in arriving at Eq. 10.59) to obtain a relation between the point variance of the radial component of turbulence and radar measurements. If turbulence is not homogeneous, $\sigma_p^2(\boldsymbol{r}, t_n)$ is still the variance at a point $\boldsymbol{r}$, but $\overline{\sigma_p^2(\boldsymbol{r},t_n)}$ is the $H_n(\boldsymbol{r}_0, \boldsymbol{r})$ weighted spatial average wind variance at each point. Then the expression for the point variance must be written as,

$$\overline{\sigma_p^2(\boldsymbol{r}, t_n)} = E_v\left[\overline{\hat{\sigma}_t^2(\boldsymbol{r}, t_n)}\right] + \sigma_{\bar{v}}^2(t_n) .$$

This is exactly the same form as Eq. (10.59), but we now have an overbar on $\sigma_p^2(\boldsymbol{r},t_n)$. This simply means that radar can only measure <u>the $\overline{H_n(\boldsymbol{r}_0, \boldsymbol{r})}$ weighted spatial average</u> of turbulence <u>at each and every point</u>.

As stated earlier (section 10.2.2.1), the variance $\sigma_{\bar{v}}^2$ does not include the variance associated with the statistical uncertainty of the estimates of $\overline{v(\boldsymbol{r}, t)}$ due to weather signal fluctuations (i.e., the variance associated with changes in the scatterers' configuration). The variance associated with the statistical uncertainty of the estimates must be subtracted from the measured variance in order to obtain $\sigma_{\bar{v}}^2$; window biases, typically associated with the measurements of $\overline{\hat{\sigma}_t^2(\boldsymbol{r}, t_n)}$ (Doviak and Zrnic, 1984, Fig. 6.8; Melnikov and Doviak, 2002), must also be taken into account.

443 section 11.4.3 — to differentiate the commonly known Bragg scatter associated with steady or deterministic perturbations from that Bragg scatter associated with random perturbations, we introduce the term "Stochastic Bragg Scatter" by replacing the second sentence of this section with:

"Perturbations in atmospheric refractive index are caused by temperature and humidity fluctuations; thus the perturbation in *n* is a random variable having a spectrum of scales. Although there is a spectrum of spatial scales, only those at about the Bragg wavelength $\Lambda_B = \lambda/[2\sin(\theta_s/2)]$ contribute significantly to the backscattered power. Because scatter is from spatial fluctuations in refractive index, the scattering mechanism is herein defined as Stochastic Bragg Scatter (SBS). Because there are temporal fluctuations as well, the scattered power is also a random variable and its properties are related to the statistical properties of the scattering medium. In this section we relate the expected…..(return to the 3rd sentence in the text)"

459 Eq. (11.124) — this equation assumes that the beam width is given by Eq. (3.2b). A more general form is

$$\rho_\perp = \frac{D_a\sqrt{2}}{\pi\gamma_1}, \qquad \theta_1 = \gamma_1\frac{\lambda}{D_a}$$

556at the end of this paragraph, "...in this section.", add: "Under far field conditions the beamwidth part of the "resolution volume weighting" term in Eq.(11.122) does not contribute significantly to the integral, but beamwidth and range resolution do contribute to the backscattered power because they multiply the integral in Eq.(11.122)."

| | | | |
|---|---|---|---|
| 460 | 0 | 2 | add the following sentence at the end of the line: $\rho_h$ is the outer scale of the refractive index irregularities, but condition (11.124) applies to the transverse correlation lengths of the Bragg scatterers. Thus, the conclusion reached in this paragraph applies if the Bragg scatterer's correlation length equals the outer scale. |
| 461 | 0 | 11 | insert after "...in space.": "This is a consequence of the greater importance of the Fresnel term relative to the resolution volume weighting term (i.e., in Eq.11.122) along the transverse directions." |
| 478 | 0 | 7 | rewrite the sentence: "Then *g*, now the directional gain (section 3.1.2) is related to…" |
| 513 | 3 | 4 | rewrite as: "…independent of all others because the shell is assumed to be many wavelengths thick and scatterers are randomly placed in the shell. |
| 547 | Index | | add: "Antenna; far field, 435-436, 459" |
| 548 | Index | | add: "Bright band, pp. 256, 268" |
| 554 | Index | | add "Melting layer, pp. 225, 255" |
| 556 | Index | | for the entry "Radome losses" add page 43. |

**Some definitions:**

Radial: A radial is the center of a band of azimuths over which the radar beam scans during the period (i.e., the dwell time) in which a number *M* of pulses are transmitted and echoes received and processed. *M* echo samples at each range are processed to obtain spectral moments (e.g., reflectivity, velocity, and spectrum width) that are assigned to the center azimuth (i.e., the “radial”). A “radial of data” is usually the set of spectral moments at all the range gates (or resolution volumes) along the assigned azimuth.